BEST AVAILABLE COPY

(54) Title: A METHOD FOR PRODUCING MOTION AND FORCE BY CONTROLLING THE TWIN STRUCTURE ORIENTATION OF A MATERIAL AND ITS USES

(57) Abstract

The present invention refers to a method for obtaining shape changes, motion and/or force in a material having a twinned structure. According to the method, a sufficiently high external magnetic field applied to the material reorients the twin structure thereby producing motion/force. The operation is possible if the magnetocrystalline anisotropy energy is higher than or comparable to the energy of the reorientation of the twin structure to produce a certain strain.
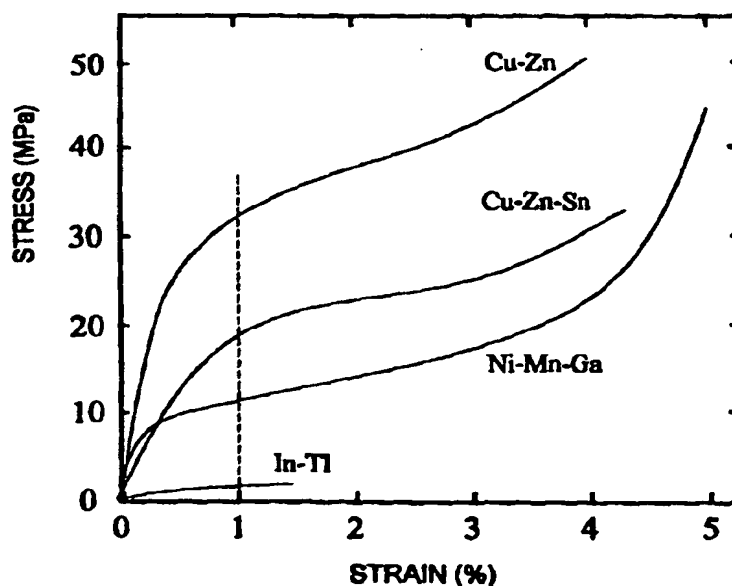
FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgystan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic	SD	Sudan
CF	Central African Republic		of Korea	SE	Sweden
CG	Congo	KR	Republic of Korea	SG	Singapore
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LR	Liberia	SZ	Swaziland
CS	Czechoslovakia	LT	Lithuania	TD	Chad
CZ	Czech Republic	LU	Luxembourg	TG	Togo
DE	Germany	LV	Latvia	TJ	Tajikistan
DK	Denmark	MC	Monaco	TT	Trinidad and Tobago
EE	Estonia	MD	Republic of Moldova	UA	Ukraine
ES	Spain	MG	Madagascar	UG	Uganda
FI	Finland	ML	Mali	US	United States of America
FR	France	MN	Mongolia	UZ	Uzbekistan
GA	Gabon	MR	Mauritania	VN	Viet Nam

A method for producing motion and force by controlling the twin structure orientation of a material and its uses

5   FIELD OF THE INVENTION

The present invention relates to a method for controlling the twin orientation by the magnetic field in a material having such a structure. The aim is to produce shape changes, motion and force by using actuators based on this method.

10

BACKGROUND OF THE INVENTION

Control of motion and force is one of the basic elements in mechanical engineering. Development of new materials has made it possible to produce motion and force using

15   special functional materials called actuator materials. The most important groups of actuator materials available are piezoelectric ceramics, magnetostrictive intermetallics, and shape memory alloys. Piezoelectric ceramics develop strains when subjected to an electric field. Frequency response of these materials is fast, but the strain amplitudes are very small, which limits their applicability. Magnetostrictive

20   materials are strained when a magnetic field is imposed on them. Certain high-magnetostrictive intermetallics (e.g., Terfenol-D, Etrema Products, Inc., Ames, IA, USA) offer strains up to 0.17 %, which is an order of magnitude higher than those of the current piezolectrics. The frequency response of the magnetostrictive intermetallics is lower than that of the piezoelectrics.

25

Shape memory metals are materials which, when plastically deformed at one temperature, can recover their original undeformed state upon raising their temperature above an alloy-specific transformation temperature. In these materials, crystal structure undergoes a phase transformation into, and out of, a martensite

30   phase when subjected to mechanical loads or temperature. The process when a mechanically deformed shape memory material returns to its original form after heating is called a one-way shape memory effect. Cooling the material subsequently will not reverse the shape change. The one-way shape memory effect is utilized in

fastening, tightening and prestressing devices. Strains of several percent can be completely recovered, and recovery stresses of over 900 MPa have been attained. In the case of the two-way effect, no deformation is required, and the material "remembers" two configurations that are obtained by heating and cooling to

5   alloy-specific temperatures. The temperature difference between the two configurations can be as small as 1 to 2 K. Materials that exhibit a two-way shape memory effect are used to develop forces and displacements in actuators. Those actuators are applied in machinery, robotics and biomedical engineering. The most extensively used shape memory materials are Ni-Ti and Cu-based alloys. A drawback

10   of the shape memory actuators is their slow response due to the thermal control (especially in cooling) and low efficiency (energy conversion), which in many alloys is only about one percent.

In order for the shape memory effect to occur, the material must exhibit a twinned

15   substructure. The shape change of the shape memory material is based on the reorientation of the twin structure in the external stress field. A two-dimensional illustration of the twin reorientation is presented in Figure 1. Figure 1 (a) shows two twin variants, denoted by 1 and 2, with equal proportions in the absence of the external stress. When the stress is applied, Figure I(b), the twin boundaries move

20   and variant 2 grows at the expense of variant 1, producing the shape which better accommodates the applied stress. The result of moving a twin boundary is thus to convert one twin variant into another. The variants which are most favorably oriented to the applied stress will grow. Ultimately, a single variant of martensite can be produced by straining a sufficient amount, as illustrated in Figure I(c). In the

25   martensite phase, the variants are usually oriented in several crystallographic directions. Therefore, complex shape changes of the material can be produced by the reorientation of the twin structure, and a full shape recovery will be obtained. Crystallographic analysis has shown that the boundaries between the martensite plates also behave as twin boundaries, i.e., the individual plates of martensite

30   themselves are twins with respect to adjoining plates. Thus the term "twin boundaries", generally refers to the boundaries between martensite plates as well as the boundaries between the boundaries within the plates (this definition also concerns the magnetically controlled twin boundaries discussed below). In some materials,

applied stress induces formation of the martensite phase whose twinned substructure is preferentially oriented according to the applied stress.

Reorientation of the twin structure is responsible for the recoverable strains of several percent in appropriate materials (e.g., close to 10 percent in Ni-Ti shape memory alloys). In some alloys the stress required to reorient the twin structure is very low. Figure 2 shows the stress-strain curves for the selected shape memory materials. It is seen that strains of 4 percent are attained by stresses of 20 to 50 MPa in most of those alloys. Stresses as low as 1 to 30 MPa result in strains of one percent. Strain energy densities needed to produce the strain of 1 percent by the reorientation of the twin variants are the areas restricted by the stress-strain curves, strain axis and the vertical dashed line in Figure 2. The strain energy densities for the alloys In-Tl, Ni-Mn-Ga (ferromagnetic Ni_2MnGa), CuZn-Sn and Cu-Zn are 10^4, 8.5×10^4, 1.1×10^5 and 2.3×10^5 J/m³, respectively.

In the following, magnetic anisotropy energy is introduced, because it plays an important role in the present invention. In ferromagnetic crystals magnetocrystalline anisotropy energy is an energy which directs the magnetization along certain definite crystallographic axes called directions of easy magnetization. Figure 3 shows the magnetization culves of single crystalline cobalt which has a hexagonal crystal structure. Its easy direction of magnetization is the parallel axis of the unit cell. The saturation is reached at a low magnetic field value in this direction, as shown in Figure 3. Saturating the sample in the basal plane is much more difficult. A magnetic field over 8000 Oe is needed for saturation. The basal plane direction is called a hard direction of magnetization. Magnetic anisotropy energy density corresponding to the magnetization processes in different directions is the area between the magnetization curves for those directions. In cobalt the energy density needed to saturate the sample in the hard direction is about 5×10^5 J/m³ (the area between the saturation curves in Figure 3). Anisotropy energy densities of magnetically hard Fe- and Co-based alloys range from 10^5 up to 10^7 J/m³ . The highest anisotropy energy densities (K1 values), close to 10^8 J/m³, are in 4f metals at low temperatures. In intermetallic compounds such as Co_5Nd, $Fe_{14}Nd_2B$ and $Sm Co_{17}$ the anisotropy energy densities at room temperature are 1.5×10^7, 5×10^7 and 3.2×10^6 J/m³, respectively.

RECTIFIED SHEET (RULE 91)
ISA/EP

SUMMARY OF THE INVENTION

This invention concerns an operational principle of the magnetically driven actuators that produce motion and force. The operation is based on the magnetic-field controlled
5　reorientation of the twin structure of the actuator material. These kinds of actuators can produce strains of several percent (as large as the shape memory materials produce). Because of the magnetic control of the new actuators, the response times are much faster, control more precise, and efficiency better than those of the shape memory materials. The new magnetically driven actuators will exhibit a great potential
10　in mechanical engineering. They will replace hydraulic, pneumatic and electromagnetic drives in many applications. Employment of these actuators leads to simpler, lighter, and more reliable constructions than use of conventional technology. Because the twin reorientation occurs in three dimensions, complex shape changes can be produced under the magnetic control. Applicability of this
15　invention is expanded by the possibility for controlling and supplying the power of the actuators at a distance. The whole machine developing a controlled motion or desired shape changes (e.g., bending, twisting, clipping, fastening, pumping fluids) may be a small appropriately shaped and preoriented piece of material. Due to the small twin size in many materials, this invention is expected to have great potential
20　also in micro- and nanotechnology.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1(a) to 1(c) show a schematic (two dimensional) presentation of the shape
25　change in martensite material as described above, namely turning of the twin variants by stress.

Figure 2 shows stress-strain (tensile) curves for single crystalline alloys In-Tl, Cu-Zn-Sn and a Ni-Mn-Ga Heusler-alloy (Ni_2MnGa) and for a polycrystalline Cu-Zn
30　shape memory alloy during the reorientation of the twin structure.

Figure 3 presents magnetization curves of single crystalline cobalt.

Figure 4 shows the principle of the present invention, namely turning of the twin variants by the external magnetic field.

Figure 4(a) presents the starting situation in the absence of the external magnetic
field;

Figure 4(b) shows the turning of the twin variant by the applied magnetic field H.

Figures 5(a) to 5(c) show the principle of the magnetic-field-induced shape change
of the twinned material which results in the shape change of the material and the
motion and force of the actuator, namely;

Figure 5(a) presents the starting situation in the absence of the external magnetic
field;

Figure 5(b) shows the step where the external magnetic field H_1 acts on the material;

Figure 5(c) presents the ultimate situation after the complete reorientation of the twin
structure by the magnetic field.

Figure 6 shows the experimental setup for studying the reorientation of the twin
structure by the magnetic field.

DETAILED DESCRIPTION OF THE INVENTION

This invention is a new method for producing shape changes, motion and/or force
in materials, based on the reorientation of the twin structure under the application
of the external magnetic field.

The present invention is described on the following pages by explaining the relevant
properties of the present invention and by referring to some figures describing the
background for easier understanding of the present invention. Reference is made
to all figures 2 to 6.

Figure 4 shows a two-dimensional illustration of the principle of the reorientation of the twin structure by the applied magnetic field. In crystalline ferromagnetic materials, magnetization vectors lie along directions of easy magnetization in the absence of the external magnetic field. This situation is shown in Figure 4(a) for

5   two twin variants. The easy direction of magnetization is parallel with the side of the unit cells of each variant. It is emphasized that the easy direction is not necessarily parallel with the side of the unit cell but it can also be any other crystallographic direction characteristic of the material.

10   When an external magnetic field is applied on a crystalline ferromagnetic material, the magnetization vectors tend to turn from the easy direction of the unit cell to the direction of the external magnetic field. If the magnetocrystalline anisotropy energy, denoted by U_k in this presentation, is high, the magnetic field strengths required to turn the magnetization off from the easy directions are also

15   high. This was illustrated for hexagonal cobalt in Figure 3. If the energy of turning the twin variants, (i.e., the energy of the motion of the twin boundaries) is low enough compared to the magnetocrystalline anisotropy energy U_k, the twin variants are turned by the external magnetic field, and the magnetization remains in the original easy direction of the turned unit cells. Figure 4b shows how the

20   unit cells of one variant are turned into another by the external magnetic field. As a result, twins in favorable orientation to the magnetic field grow at the expense of the other twins, as shown in Figure 5.

Figure 5(a) represents the starting situation in the absence of the field when the

25   twin variants with equal proportions are present. Magnetization is aligned parallel to one side of the unit cell in each variant. In the figure, only a part of the magnetization vectors is shown. In this illustration twins are assumed to be consisted of only single ferromagnetic domains (recent TEM studies have revealed that twins in some ferromagnetic martensites e.g Fe-Pt can be

30   consisted of two magnetic domains whose domain wall crosses the twin.)

Figure 5(b) shows how the unit cells whose easy direction of magnetization are different from the direction of the external magnetic field are turned so as to line

RECTIFIED SHEET (RULE 91)
ISA/EP

up with the field direction. This results in the growth of the favorably oriented twin variant and the decrease of the other variant. Ultimately, only one twin variant may remain, as shown in Figure 5(c).

5   The reorientation of the twin structure described above results in the shape change of the material, which can produce motion and force in the magnetically controlled actuators made from this material. It is possible also to produce complex shape changes because the reorientation of the twin structure occurs in three dimensions. The original dimensions of the actuator material may be
10   restored by eliminating the field, or by turning the field to another direction. Effects of the external magnetic field on the orientation of the martensite unit cells can cause the directed motion of martensite-martensite and austenite-martensite interfaces, which may also be utilized in actuators. In that case the preferentially oriented twinned martensite grows at the expense of the
15   parent phase. This growth can also be reversible.

The magnetic-field-control of the reorientation of the twin variants is expected to produce recoverable strains of several percent in appropriate materials (analogous to stress-induced recoverable strains in the shape memory alloys).
20   To reach a certain magnetically induced strain, it is necessary that the magnetocrystalline anisotropy energy U_k of the material is larger than or comparable to the energy needed to reorient the twin variants to achieve this strain. The latter energy, defined as the energy of the reorientation of the twin structure, and denoted by E_{tw} includes also strain and dissipation energy terms
25   related to the shape change of the material. In the actuator applications, U_k must be greater than the sum of E_{tw}, and the work of the actuator. The work term may be positive or negative. If the work is negative, the external stress may assist the reorientation of the twin structure and decrease the magnetic field energy required. For the actuator to be able to operate, it is necessary that the magnetic
30   field energy that controls the actuator must be larger than the sum of E_{tw}, and the work of the actuator. The higher the U_k is, the larger the magnetic field energies are which can be converted to mechanical work of the actuators and, hence, the higher forces are attained.

In the following, the magnitudes of the anisotropy energies will be compared with the energies of the reorientation E_{tw} in different materials. As it was shown in Figure 2, energy densities E_{tw} for producing strain of 1 percent in the selected martensitic shape memory alloys are between 10^4 and 2.3×10^5 J/m^3. On the other hand, there is a diversity of materials available in which magnetic anisotropy energy densities are 10^5 to 10^8 J/m^3. Some examples (Co-, Fe- and rare-earth-based alloys) were given above. Anisotropy energy densities of some materials are even four orders of magnitude larger than the energy densities E_{tw} for the reorientation of the twin structure, e.g., in In-Tl. This large difference in energies U_k and E_{tw}, reveals that there is a great potential for finding optimal materials that combine high anisotropy energy and low E_{tw}.

In some ferromagnetic martensites twin boundaries are highly mobile under application of stress. It was shown in Figure 2 for the ferromagnetic martensitic Ni_2MnGa (single crystalline) that stresses as low as 10 to 20 MPa in direction [100] cause the reorientation of the twin variants, resulting in the recoverable strains of 4 percent. To reach a strain of 1 percent in this alloy by the magnetic-field induced reorientation of the twin structure, anisotropy energy must be larger than the energy of the reorientation of the twin variants E_{tw}, 8.5×10^4 J/m^3, according to Figure 2. This value is quite low and, therefore, the magnetically induced strains are expected to be possible in this material. In most ferromagnetic shape memory alloys available to date and other iron-based alloys that exhibit a twinned substructure, stresses for aligning the twins are higher, even above 100 MPa. However, their magnetocrystalline anisotropy energies are often high enough for producing magnetic-field-induced strains based the reorientation of the twin structure, which has been experimentally demonstrated in some alloys. For example, in a material in which the stress of 100 MPa would be needed to reorient the twin structure producing a strain of 1 percent, E_{tw} is calculated to be 5×10^5 J/m^3 (assuming that stress increases linearly with strain). In order to produce the same strain by the magnetic-field-induced reorientation of the twin structure, anisotropy energy must be larger than or equal to 5×10^5 J/m^3. This anisotropy energy value is the same as that of cobalt and is attainable in many Fe- and Co-based alloys.

materials. To produce the strain of the same amount by the magnetic field, anisotropy energy density of 2.5×10^6 J/m^3 is needed. This anisotropy energy value is attainable in suitable alloys, because the highest anisotropy energies at room temperature are even 20 times larger. It is emphasized that only estimations obtained from some

5 material classes are used in this presentation for evaluating the magnetocrystalline anisotropy energies, because the anisotropy energy values for the twinned materials with low E_{tw} cannot be measured using saturation magnetization measurements (see Fig. 3). The reason is that the magnetization does not turn in the applied field to the hard direction of the unit cells, but the saturation is reached by turning the twin

10 variants (together with the magnetization vectors) at lower magnetic field levels. The magnetization measurements should be made on single variant samples which are in many cases not possible to produce.

The development is focused in finding new ferromagnetic materials which exhibit high

15 anisotropy energy and low E_{tw}. The best materials may combine high anisotropy energies coming from the rare earth metals and highly glissile twin boundaries of a suitable twinned phase. Also Co- and Fe-based shape memory materials in which the martensitic lattice is close-packed hexagonal or cubic are promising and are being developed. The role of the interstitial atoms, especially nitrogen may be important,

20 because they often increase the anisotropy energy and strengthen the alloy mechanically, which favors twinning as a deformation mechanism and prevents permanent slip. One interesting group of the magnetically controlled actuator materials are Heusler alloys (e.g., Ni$_2$MnGa-type) in which Mn is responsible for their ferromagnetic properties.

25

The velocity of the twin boundaries in many materials is very fast, even a fraction of the speed of sound. This means that the magnetic-field-induced strokes are very fast in suitable actuator materials, and the actuators can operate at high frequencies.

EXAMPLES

The reorientation of the twin structure by the magnetic field was experimentally studied in Fe-Ni-Co-Ti, Fe-Ni-C and Fe-Mn-N -based alloys. These materials are
5   ferromagnetic and exhibit a twinned microstructure. The anisotropy energies were measured to be typically about 5×10^5 J/m^3 for Fe-Ni-Co-Ti alloys and 2×10^5 J/m^3 for Fe-Ni-C alloys. These are expected to be sufficiently high for producing the magnetic-field-induced strains based on the reorientation of the twin structure. The experimental setup employed in the present studies and examples of the
10   measurements are shown in the following.

The experimental setup

The principle of the equipment for studying the effects of stress and magnetic field
15   on the twin structure is shown in Figure 6. This equipment makes it possible to apply axial and torsional stresses on the sample, and to measure the corresponding strains. The sample 6 was fixed in two coaxial supporting tubes 1 and 2. Tube 1 was fixed and tube 2 was used for straining the sample. The sample chamber was surrounded by a coil 7 for applying the magnetic field to the sample. In alternating magnetic field,
20   a frequency response of the magnetically induced strains was measured at low frequencies. At higher frequencies, the frequency response was measured using a strain gauge attached on the sample. In these measurements bar 2 was removed. This arrangement was also used in experiments made on bent samples. The strain gauges were placed on both sides of the bent sample. The changes of strains caused
25   by the applied magnetic field were measured in static and alternating magnetic fields.

Arrangements for measuring electrical resistivity and magnetic susceptibility were also made on the sample holder, as shown in Figure 6, namely the four point contacts 3 for resistivity and the coils 5 for susceptibitity measurements. The sample chamber
30   was immersed in liquid nitrogen or liquid helium, and the temperature could be controlled between 4 and 600 K using a heater 4.

Dissipation attributed to the motion of the twin boundaries and the martensite

interfaces was also studied with this equipment. The amount of martensite was detected using electrical resistivity and magnetic susceptibility measurements. Also Mössbauer spectroscopy was used to determine the phase fraction of martensite. Mössbauer spectroscopy was more suitable for the present studies than X-ray

5　　spectrocopy, because Mössbauer measurements are not sensitive to the texture of the sample.

EXAMPLE 1

10　　An alternating twisting deformation was applied to the sample, and the vibration damping capacity was measured. These experiments revealed that twin boundaries (as well as the interfaces between austenite and the twinned martensite) were highly mobile. The measurements were made at strain amplitudes 10^{-6} - 10^{-3}.

15　　EXAMPLE 2

Magnetically induced strains were measured on the bent samples. In the beginning, the martensitic sample was bent mechanically. During this deformation one side of the sample was elongated and the other side was contracted. As a result, the twin

20　　structures on different sides of the samples were oriented in different ways, leading to the different proportions of twin variants, to accommodate compressive and tensile stresses. It was confirmed that the amount of martensite was the same on both sides of the sample. When the magnetic field was applied to the bent sample, the field-induced strains appeared, and they were in opposite directions on different sides

25　　of the sample. On the side which was initially elongated by the mechanical stress, the magnetic field induced a contraction and on the other side the field induced an elongation. For example, when a magnetic field of 1 kOe was applied on a slightly bent twinned martensitic Fe-Ni-C sample of 1 mm in thickness, the difference in strains between the two sides was 2.2 x 10^{-5}. This value is higher than

30　　magnetostriction of this material. Magnetostriction cannot be the explanation for this effect, because it cannot cause strains of the opposite directions in different sides of the sample, and secondly because its magnitude is too small.

RECTIFIED SHEET (RULE 91)
ISA/EP

The initial mechanical deformation was also made by twisting. The twisting deformation results in a specific reorientation of the twin structure. When the magnetic field was applied on this structure, the torsional strains appeared.

5   The magnetically induced strains observed on the bent and twisted samples could be attributed to the reorientation of the twin structure or the growth of the preferentially oriented martensite. The present experiments were made, however, above M_d temperatures of the martensite. At temperatures above M_d, the formation of martensite is not thermodynamically possible, which confirmes that the magnetically controlled

10   reorientation of the twin structure causes the strains observed.

The bending and twisting experiments also suggest that more complicated shape changes can be produced using external magnetic field.

15   EXAMPLE 3

X-ray diffraction patterns of martensite were measured in magnetic fields perpendicular to and parallel to the surface of the sample. The intensities of the individual Bragg peaks correlate with the fraction of the twin variants in the diffraction

20   condition. The measurements showed changes in peak intensities which were attributed to the magnetically induced twin reorientation of the martensite. The peak intensities were observed to change also in alloys in which only the inner parts of martensite plates are twinned. The outer parts of the plates consist of dislocation cells and tangles. Therefore, the interfaces between the martensite and austenite

25   phases are immobile in those alloys, and the magnetic-field-controlled growth of the martensite plates with preferentially oriented twin variants cannot serve as an explanation for the effects observed.

INDUSTIAL APPLICABILITY

30

The new actuators based on the present invention exhibit a great technological and commercial potential. No other method for producing motion and force based on the material properties can develop such a combination of high strains, forces, speed

and precision as these new actuators. Potential applications are fuel injectors, high-pressure pumps, actuators of active vibration control, active springs, valve lifters and controllers, robots, precision tooling and linear motors. Actuators can also be integrated with sensing and control capabilities. Those systems, named adaptive,

5   active or smart structures, are becoming general in modern machine design. Sensing the operational parameters of a machine in real time, and responding to the environmental or internal changes in a controlled manner makes it possible to attain more optimal operation, minimal energy consumption, enhanced life-times of the structures and lower maintenance costs. Adaptive structures are applied in aerospace,

10 automotive, marine and civil engineering, precision machining and production engineering. The most widely used actuators are pneumatic and hydraulic systems, electromagnetic drives and actuator materials such as piezoelectrics, magnetostrictive intermetallics and shape memory alloys. Progress of the adaptive structures has been severely retarded by the absence of the high speed and large stroke actuator

15 materials. The new materials based on the present invention may lead to a great advance in the technology of the adaptive structures and modern engineering.

Because the reorientation of the twin structure occurs in three dimensions, complex shape changes including tension, bending and twisting of the samples can be

20 produced by the magnetic field. This significantly expands the applicability of the present invention in many fields of engineering and machinery. Other magnetically driven actuators based on magnetostriction do not have such properties. The actuator/machine developing a controlled motion or certain shape changes by the magnetic field may be an appropriately shaped and preoriented piece of material.

25 By designing the shape and the initial twin structure properly, the actuator can repeat complex shape changes when the intensity of the magnetic field is cycled. The trace of the motion of the actuator can be changed by changing the direction of the field.

The method of the present invention makes it possible to control the operation of

30 the actuators remotely. Remote control is suitable, for example, in biomedical applications like in medical instruments, artificial organs, such as a heart. A large number of actuators could operate simultaneously using a common magnetic-field-control. Even if the magnetic field were the same for all of the actuators, the actuators

could be made to operate in different ways depending on the initial twin structure made in the material.

5   Because the twin structure is expected to be controlled also in thin films, wires and particles, the actuators based on this invention may also be applied in micro and nanotechnology. The actuators could be even the size of the individual twins. The nanoactuators could utilize, e.g., quantum tunneling currents for the position sensing.

10 The present invention is a new method for producing motion, force and shape changes using electric energy. Actuators based on this method may exhibit a potential to become the most widely used electric drives after motors and other devices based on electromagnetic forces. In several fields of engineering, the new actuators are expected to replace the conventional electric devices due to their better performance, greater reliability and lower costs. The largest potential of the present invention may 15 lie, however, in new applications which only the technology based on this invention makes possible.

CLAIMS

1. A method for controlling the orientation of the twin structure in a material having a twinned structure, comprising

5 applying to the material a magnetic field which is of the direction and of the magnitude enough for the reorientation of the twin structure of the material, to produce thereby shape changes of the material and motion and/or force.

2. A method according to claim 1, wherein the magnetic field is directed on the

10 material in the direction of the easy magnetization of the desired twin orientation.

3. A method according to claim 1, wherein the magnetic field is directed on the material in such a direction that produces a desired shape change or motion of the material due to the reorientation of the twin structure.

15

4. A method according to claim 1, wherein the magnetic field is directed on the material in the direction differing from the direction of the easy direction of magnetization of the twin variants to produce bending or twisting of the material.

20 5. A method according to claim 1, wherein the magnetic field is directed on the material in a changing direction and/or with changing magnitude as a function of time.

6. A method according to claim 1, wherein the magnetocrystalline anisotropy energy of the material is higher than or comparable to the sum of the energies of the

25 reorientation of the twin structure required to produce a desired shape change and the work done by the material.

7. A method according to claim 1, wherein the energy of the magnetic field applied on the material is higher than or comparable to the sum of the energies of the

30 reorientation of the twin structure required to produce a certain shape change and the work ofthe material.

8. A method according to claim 1, wherein the material is ferromagnetic.

9. A method according to claim 1, wherein the material is martensite.

10. Use of the method according to any of the preceding claims to use an actuator wherein the shape change, motion and/or force of the actuator is affected by the present method.

11. Use of the method according to any of the preceding claims 1 to 9 to use actuators which are controlled, and the power of which is provided remote from the actuators.

12. Use of the method according to any of the preceding claims to use actuators in micro- and nanotechnology, in example the actuators made from twinned thin films, wires or particles.

13. Use of the method according to claim 1, wherein the actuator is for pumps, injectors or similar devices for transferring material, especially fluid.
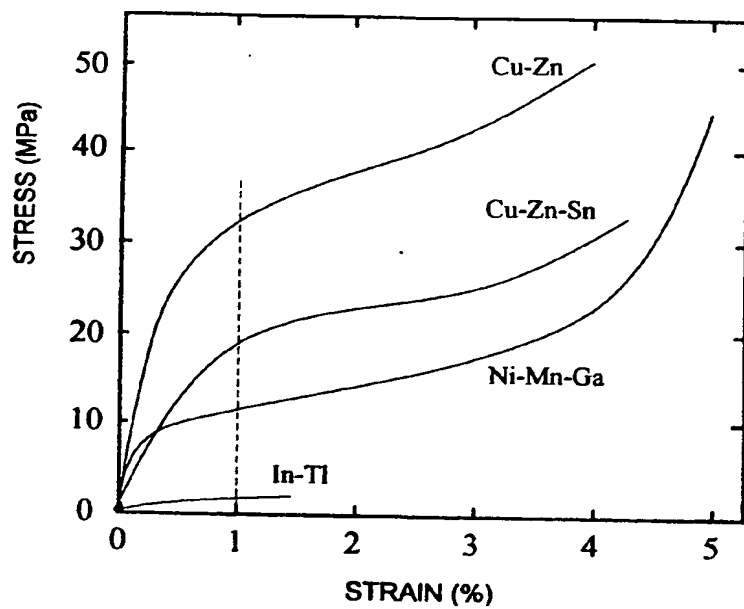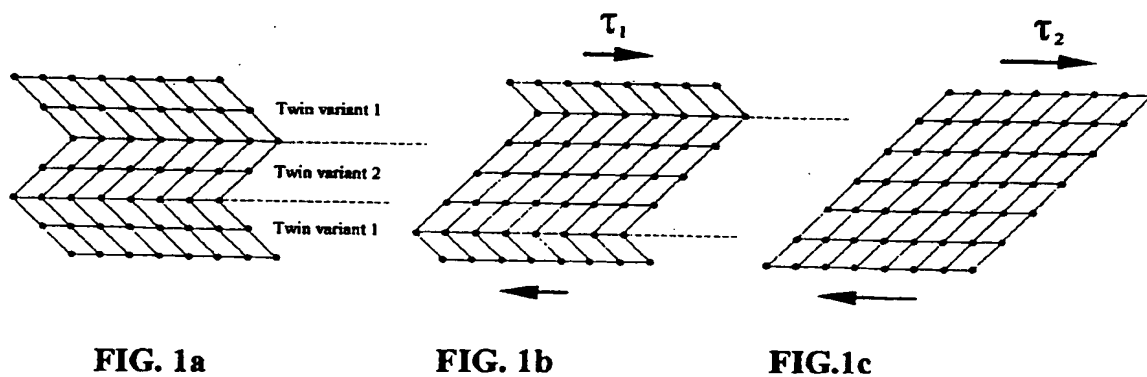
FIG. 1a   FIG. 1b   FIG.1c
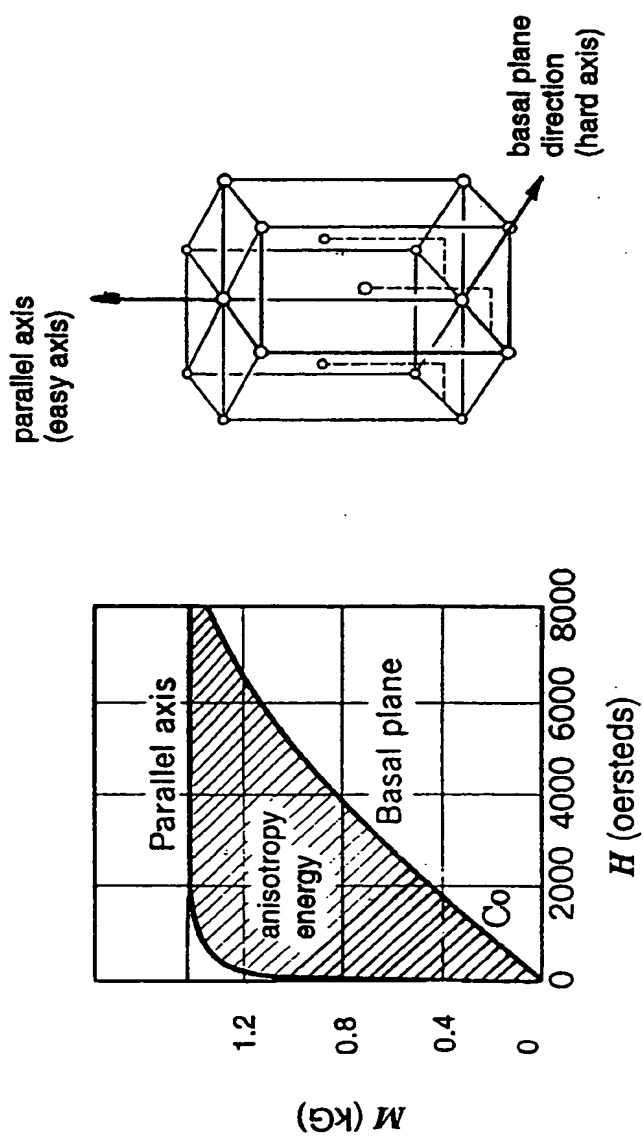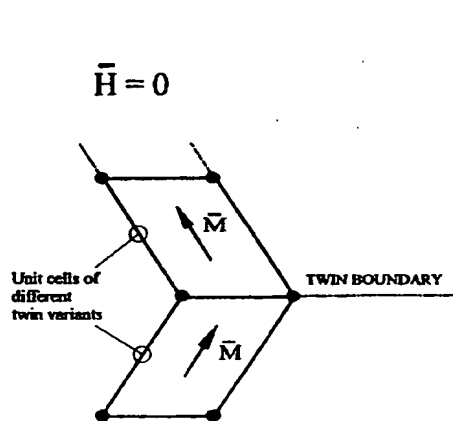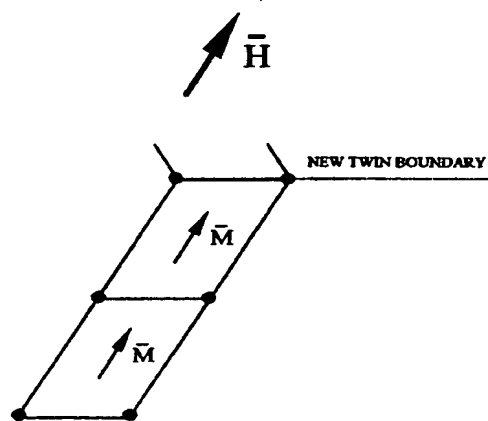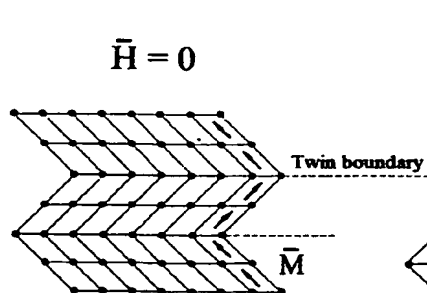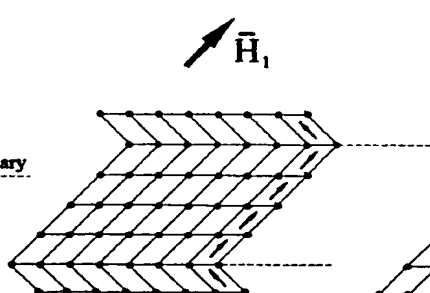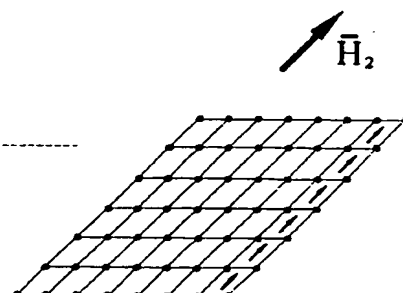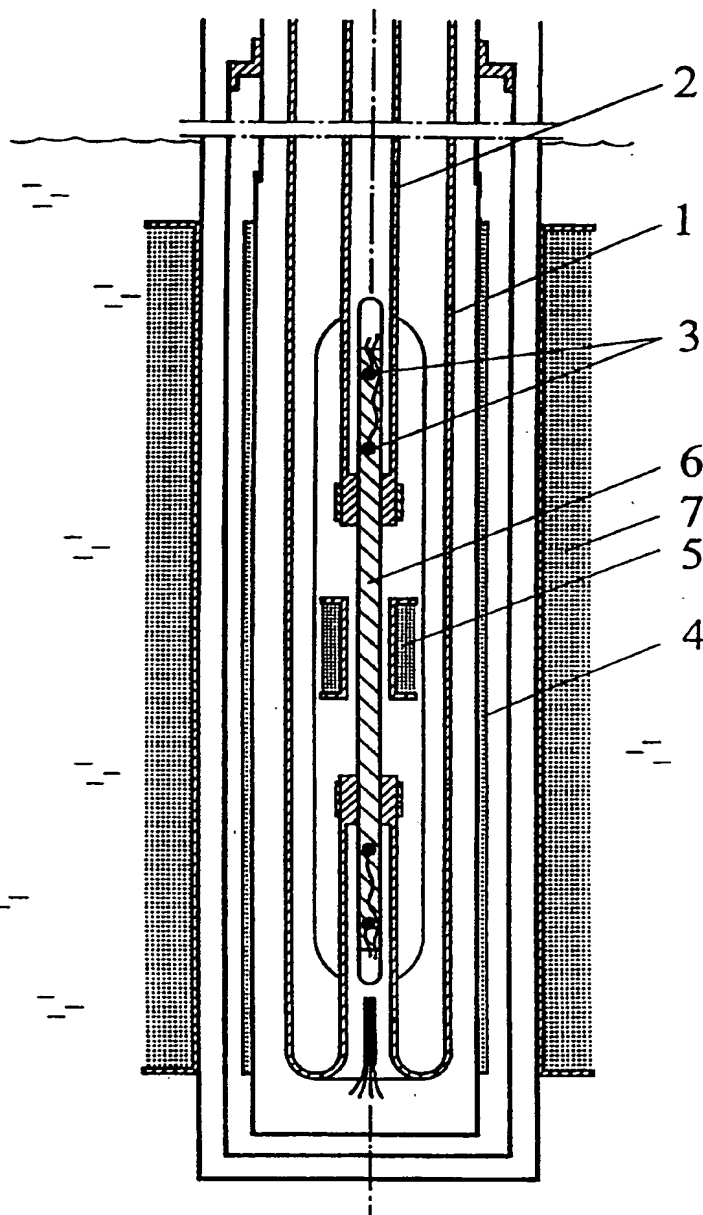
FIG. 2

SUBSTITUTE SHEET (Rule 26)

FIG. 3

$\bar{H} = 0$

$\bar{H}$

Unit cells of
different
twin variants

$\bar{M}$

$\bar{M}$

TWIN BOUNDARY

NEW TWIN BOUNDARY

$\bar{M}$

$\bar{M}$

FIG. 4a   **FIG. 4b**

$\bar{H} = 0$ $\bar{H}_1$ $\bar{H}_2$

Twin boundary

$\bar{M}$

FIG. 5a   **FIG. 5b**   **FIG. 5c**

SUBSTITUTE SHEET   (Rule 26)

4/4

F I G. 6

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 6   H01L41/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DATABASE WPI Section Ch, Week 9146 Derwent Publications Ltd., London, GB; Class L03, AN 91-337460 XP002018991 & SU 1 611 980 A (AS UKR METAL-PHYS) , 7 December 1990 see abstract ---	1
X	SCRIPTA METALLURGICA, AUG. 1985, USA, vol. 19, no. 8, ISSN 0036-9748, pages 973-976, XP000609308 KAKESHITA T ET AL: "Magnetoelastic martensitic transformation in an ausaged Fe-Ni-Co-Ti alloy" see the whole document --- -/--	1

[X] Further documents are listed in the continuation of box C.   [ ] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 November 1996	29. 11. 96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Pelsers, L

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	JOURNAL OF MATERIALS ENGINEERING AND PERFORMANCE, vol. 5, no. 3, 1 June 1996, pages 405-409, XP000593943 ULLAKKO K: "MAGNETICALLY CONTROLLED SHAPE MEMORY ALLOYS: A NEW CLASS OF ACTUATOR MATERIALS" see the whole document -----	1